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Performance Evaluation of the Solar Building Test Facility

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SUMMARY

NASA's Solar Building Test Facility (SBTF) consists of a 4645-m^2 (50 000-ft^2) office building designed to accept solar-heated water for operation of an absorption air conditioner and a baseboard heating system and an adjoining 1176-m^2 (12 660-ft^2) solar flat-plate collector field with a 114-m^3 (30 000-gal) storage tank. The SBTF has been in operation since 1976 and has demonstrated that solar cooling is technologically feasible. Fifty-seven percent of the energy required for heating and cooling on an annual basis was provided by the solar system. The average efficiency of the solar collectors was 26 percent over a 1-year period. During the same period, 46 percent of the solar energy collected was actually utilized. The average utilization rate was 82 percent for the months when thermal energy consumption was exclusively for cooling.

The 82°C (180°F) water typically available from the solar field resulted in chilled water from the absorption machine with higher temperatures than the 7°C (45°F) design temperature normally used to cool office buildings. Nevertheless, an acceptable working environment could be provided by decreasing the dry bulb temperature in the building to compensate for the resultant high humidity.

The general performance of the SBTF and its subsystems and components over the 4-year operational period is discussed, and data are provided for a typical 1-year period.

INTRODUCTION

The use of solar energy to heat buildings is rapidly becoming an accepted concept; however, the use of solar energy to provide cooling is proving to be a much greater challenge. The Solar Building Test Facility (SBTF) represents an effort by NASA to advance the technology for heating and, especially, cooling office buildings with solar energy. This would promote year-round use of solar collectors rather than seasonal use for heating only.

The technical problem with solar cooling systems is that the output temperature produced by typical flat-plate collectors is very near the practical lower limit of the temperature needed to drive absorption chillers. For high efficiencies in the solar collectors, discharge temperatures must be kept low; however, water temperatures too low result in excessive chiller capacity reductions. The effect of water temperature (output from collectors and input to the absorption unit) on the capacities of solar collectors and absorption chillers is illustrated in figure 1. As water temperature increases, the capacity of the chiller increases; however, the effective capacity of the collectors decreases with increasing water temperature. As a result and as shown in figure 1, at given conditions a natural balance point is achieved with a water temperature of approximately 88°C (190°F) and a system capacity of 316 kW (90 tons).

The SBTF, shown in figure 2, is an office building and solar field. The office building, the Systems Engineering Building (SEB), accepts heat from an adjoining solar collector field to both heat and cool the building. The solar energy system is biased toward the cooling cycle because of energy use patterns in an office building and climatic conditions at the test facility location. The SBTF was designed as an experimental facility to (1) test systems components, including high-performance flat-plate collectors; (2) test performance of a complete solar heating and cooling system; (3) investigate component interactions; and (4) investigate durability, maintenance, and reliability of components. The solar system was designed to provide a major portion of the office building's heating and cooling requirements.

When this project originated in 1973, it was decided to substitute an absorption chiller driven by solar energy for a centrifugal-type chiller as the cooling system in a new office building scheduled for construction at Langley Research Center. The project design was assisted by use of NECAP, NASA's Energy-Cost Analysis Program described in reference 1, for determining air conditioning component sizing, collector tilt angle, and other building and system features. Construction was completed, and the SBTF became operational in May 1976.

This report evaluates the performance of the heating and cooling system over a 4-year period of operation, with data provided for a particular representative 1-year period from September 1977 through August 1978. The dynamics of the system's components are evaluated as well as the performance of the overall system in regard to such parameters as efficiency of the solar collectors and percentage of thermal energy provided by the solar system.

Data are reported in both S.I. Units and U.S. Customary Units. Original measurements were made in U.S. Customary Units.

Use of trade names or manufacturers' names does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by NASA.

DESCRIPTION OF FACILITY

The SBTF is located at the NASA Langley Research Center in Hampton, Virginia, latitude 37° N, longitude 76.4° W. The test facility consists of the office building and an adjoining 1176-m^2 (12 660-ft^2) solar collector field with a 114-m^3 (30 000-gal) tank for energy storage. The measured horizontal solar energy at the test site is 4.8 GJ/m^2-yr (420 000 Btu/ft^2-yr), about 75 percent of theoretical "no-cloud" insolation.

The piping/control system is diagrammed in figure 3. The system is instrumented so that 152 different temperatures, pressures, and flow rates are measured and recorded every 5 minutes during the day and once per hour at night. Both pneumatic and computer-based monitoring equipment is used to obtain operating data on the building, absorption chiller, storage tank, and collectors. Reference 2 offers additional information on the design and construction of the SBTF.

Building

Construction.- The office building is a 4645-m^2 (50 000-ft^2) single-story structure providing office space for over 300 engineering personnel. Walls are made of concrete block with brick-veneer facing. Inside surfaces of exterior walls are insulated and covered with gypsum board. Twenty percent of the wall space in occupied areas is composed of heat-absorbing glass. The ceiling is 19-mm (3/4-in.) acoustical, lay-in tile, which forms an overhead cavity used as a return plenum for the air conditioning system. The roof is metal deck covered with 76 mm (3 in.) of cellular insulation and roofing. The lighting is fluorescent, designed for 40.9 W/m^2 (3.8 W/ft^2). The building electrical load for lighting and receptacles is actually 28.1 W/m^2 (2.6 W/ft^2) throughout the gross building area after lighting reduction and relamping with lower wattage lamps was accomplished. The building was designed to conserve energy by using methods such as extra insulation, installing tinted and recessed windows, flowing return air through the light fixtures, using outside air for air conditioning when the ambient air temperature is appropriate, and allowing large temperature excursions within the building during working and nonworking hours.

Environmental system.- The SEB is cooled by a central-station, variable-volume air conditioning system that operates between 13 200 and 21 700 L/s (28 000 and 46 000 cfm). The plenum over the ceiling is used as a return air path. Chilled water for cooling is provided by a 612-kW (174-ton) lithium bromide absorption machine having a 5.1-kW circulating pump. The capacity of the absorption machine for air conditioning is a function of the incoming hot water temperature (see fig. 1).

A hot water perimeter baseboard system provides heating. The baseboard can produce 146.5 kW (500 000 Btu/hr) using 77°C (170°F) water and 18°C (65°F) space temperature. Some additional heat can be obtained from unit heaters located in the ceiling plenum.

Hot water for operation of the absorption chiller and the baseboard heating is supplied by the solar field (either directly from the collectors or from the storage tank) or supplemented by a conventional steam-to-hot-water converter. This converter system can fulfill 100 percent of the building's energy requirements if needed.

The equipment for heating, air conditioning, and ventilating the SEB is located in a 279-m^2 (3000-ft^2) second-story structure ("penthouse") near the center of the building. The control center and data-handling system for the SBTF are also housed there.

Solar Field

Solar collectors.- Different types of flat-plate collectors are installed on nonadjustable wooden stands facing directly south and tilted 32° from the horizontal. The collector field is at ground level rather than on the building roof to facilitate access for inspection, monitoring, and modifications.

Originally there were 12 rows, each containing 51 collectors (except for row 3, which contains 42 collectors), totaling 603 collectors in the solar field. A 13th row was added in 1979. The original installation of collectors in the solar field is listed in table I along with the installation existing as of July 1980. Figure 4 is a photograph of the collectors in the solar field. Reference 3 contains information on the construction of the solar collectors and their performance during the first few months of operation.

The water flow through each row of collectors is modulated so that each type of collector raises the water temperature equally to a desired level. The efficiencies of different collectors can thus be compared. As new types of collectors, such as tracking collectors and vacuum tube collectors, have become available, they have been incorporated in the field for testing.

Storage.- The hot water storage facility is a surplus liquid oxygen tank with a capacity of 114 m^3 (30 000 gal). The tank has a vacuum jacket which minimizes thermal loss. The tank's internal dimensions are 2.9 m (9.5 ft) in diameter and 16.8 m (55 ft) in length. Full length headers are provided at the tank bottom and just below the water level. The tank is also used as the system's expansion tank. Since the air volume in the tank is not adequate for expansion of water due to temperature variations, air is either brought into or taken out of the tank to limit the system's pressure excursions. Service air from a pressure-reducing station is used to establish a minimum tank pressure at 206 kPa (30 psi). When pressure exceeds 275 kPa (40 psi) due to temperature, air is relieved through a pressure-reducing valve.

Short-circuiting of water flow between the headers has been a major problem in obtaining energy from the storage tank. A single horizontal baffle was installed in 1979 to minimize short-circuiting.

Water treatment.- The water piping for the solar collector system is steel and copper. The commercially available collectors are made of steel and aluminum, with some copper collectors added in 1979. Collector corrosion, encouraged by dissimilar metals in the system, was a major concern. After construction, the hot water system was cleaned. Mill scale, dirt, oils, fluxes, and other impurities were removed using a solution containing 0.4 percent trisodium phosphate, 0.4 percent sodium metasilicate, and 0.04 percent low-foaming detergent (Dash[1]). This mixture was circulated using the system's pumps at temperatures of 60°C to 71°C (140°F to 160°F) for 1 day. The aluminum collectors were cleaned separately with a similar solution which contained only half of the above concentration of trisodium phosphate. The cleaning mixture was drained, and flushing was performed three times to eliminate the cleaning material.

Scale control in the collectors was also considered. This was necessary because the local water supply has a total hardness of 75 ppm (measured as calcium carbonate) and because the collectors have high surface temperatures where calcium carbonate scale could build up. For these reasons, softened water, from which calcium has been eliminated, was used to fill the system.

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[1]Dash: trade name of Procter & Gamble Co.

Metal in the collectors was protected from the oxygen in the hot water by a chemical film. The water in the system was to be treated with sodium chromate and sodium dichromate to obtain a chromate level of 800 to 1000 ppm and a pH of 8.0. After the initial chemical charge of sodium chromate, the chromate level was 900 ppm. Therefore, only enough sodium dichromate was added to obtain 1000 ppm of chromate. This resulted in a pH of 9.4, which was corrected to 8.0 using boric acid. The pH correction is especially critical since aluminum was used in the system. Some sodium metasilicate was added to provide additional aluminum protection. The time period between cleaning, filling, and treatment was kept to a minimum, since corrosion begins immediately after the cleaner is removed.

In the presence of the high chromate concentration and high temperature, there was concern that pump seals would experience early failure. Protective procedures included a 5-μm filter on the water seal purge line and a few feet of uninsulated copper tubing in the line to reduce the temperature of the flushing water to the pump seals.

<u>Control concept</u>.- The general piping system is constructed and valved in such a way that flow can be varied or altered and studied. Four conditions are possible for the solar system:

1. Balanced, in which water is delivered directly from the collectors to the absorption chiller or baseboard heating system

2. Storage, in which hot water from the collectors is taken from the water loop and delivered to the top of the storage tank; the cooler water at the bottom of the tank flows to the pump and then back to the collectors

3. Reclaim, in which the return "used" water from the building is delivered into the bottom of the storage tank, and the hot water from the top of the storage tank is delivered to the building

4. Freeze protection, in which solar-heated water is circulated through the collectors to keep temperatures above freezing; a glycol freeze protection system was added for the 1979-80 winter season.

The most desirable operation is to obtain hot water directly from the solar collectors. This flow pattern prevents temperature losses from interaction with heat exchangers or storage tanks and keeps chiller capacity high. If the temperature of the water from the solar collectors is too low, hot water is taken from the storage tank. If neither of these sources is adequate and supply temperatures are below 77°C (170°F), all thermal energy is obtained from the supplemental source. When water of sufficient temperature is again available in the solar field, the system automatically changes back to obtaining hot water from this source. This "flip-flop" arrangement was used because "topping off" of solar-heated water (running it through the converter used as the supplemental energy source) would result in higher temperatures into the collectors, causing a decrease in collector efficiencies.

PERFORMANCE EVALUATION

Overall System Performance

Table II summarizes the performance of the solar system during a typical 12-month period of operation, from September 1977 through August 1978. During the 1-year period, 57 percent of the energy required for heating and cooling the SEB was provided by the solar system, with 43 percent provided by the backup system. On a monthly basis, the portion of required thermal energy provided by the solar system varied from lows of 33 and 35 percent in January and February, respectively, to 100 percent during November and April. Of the 1176 m^2 (12 660 ft^2) of solar collectors available, 1064 m^2 (11 450 ft^2) were operational from September 1977 through April 1978. From May 1978 through August 1978, the operational solar field was further reduced to 974 m^2 (10 480 ft^2) due to maintenance and repairs. This had the effect of lowering the percentage of required thermal energy supplied by the solar system. Total electrical and thermal energy consumption of the SEB during the 12-month period of data collection shown in table II was 0.97 GJ/m^2-yr (85 400 Btu/ft^2-yr).

Shown in table III is a breakdown of the thermal energy consumption in the SEB for heating and cooling on a monthly and annual basis. Over the 1-year period, 81 percent of the thermal energy consumed was for cooling, and 19 percent was for heating, justifying the system design bias toward cooling in the SBTF. Heat was required during 8 of 12 months (October-May). Air conditioning was required in 9 of 12 months, from March through November.

The utilization rate of collected solar energy is given in table IV. Over the 12-month period, 46 percent of the energy captured by solar collectors was actually used. Monthly use rates varied widely from a low of 8 percent during April to a high of 85 percent during June. The average utilization during the months when no heat was needed and the energy usage reflected only cooling consumption (June, July, August, and September) was 82 percent.

For the month of April, when the highest amount of energy was collected, the building used little energy, and thus the energy utilization percent was very low. During this period, thermal losses were high due to high system temperatures; in fact, some energy had to be rejected by circulating water through the collectors at night to keep the collector temperature under 110°C (230°F) during the day.

Building environment with cooling.- On work days when cooling is required, the building cooling operation starts at 7:30 a.m. The absorption chiller energy comes from the storage tank or the supplemental energy source because the water in the solar collectors has not reached a sufficient temperature. Typically, by 10:30 a.m. (DST), the water in the collectors reaches 79°C to 82°C (175°F to 180°F), at which point the system is switched to operate directly from the solar collectors. With normal Sun, the system operates from the solar field for the remainder of the work day (until 4:30 p.m.).

The water temperature of 82°C (180°F) available from the solar field resulted in higher chilled water temperatures of 13°C to 16°C (55°F to 60°F) from the absorption machine than the 7°C (45°F) chilled water temperature normally used for cooling and dehumidifying office buildings. Nonetheless, an acceptable working environment was provided by compensating for the resultant high humidity by lowering dry bulb temperatures in the SEB about 0.5°C (1°F) for each 10-percent rise in relative humidity, up to 70 percent. When the humidity reaches this point, supplemental energy is used for environmental control.

A satisfactory environmental condition has been provided using 1 ton of cooling per 46 m^2 (500 ft^2) of building. This is about half of the capacity generally designed into conventional office buildings. This lower capacity has been made feasible by (1) maintaining a low fresh air ventilation rate of 708 L/s (1500 cfm) or 2.4 (L/s)/person (5 cfm/person), (2) allowing temperature conditions to vary or "ramp" (increase during the workday) within the building, and (3) letting humidity rise while compensating by using lower temperatures in occupied areas, as mentioned previously.

The psychrometric chart in figure 5 shows the range of temperature and humidity conditions during 99 percent of the actual working hours in 1977 compared with the ASHRAE Standard 55-74 comfort zone (ref. 4).

During the summer, the building exceeded ASHRAE comfort standards only 5 percent of the working hours. When ASHRAE standards were not met, it was usually due to the relative humidity limit being exceeded. Thus, it was determined that an absorption system can use chiller water temperatures higher than the normal design temperature of 7°C (45°F) and that a working environment can be satisfactory, or at least acceptable, at much higher humidities than the 50 percent design limit used in the past if compensation is made in the form of lower temperatures.

<u>Building environment with heating</u>.- For heating, 20 percent of the working hours were below the ASHRAE comfort zone. However, prior to 1979, the low temperature limit for the SEB was 20°C (68°F) in accordance with federal guidelines established by a Federal Energy Office memorandum dated January 17, 1974 (and enclosed Federal Management Circular 74-1, Att. C). The temperature in the building was below this temperature (20°C or 68°F) only 3 percent of the working hours.

Several factors contributed to the lower-than-desired temperatures in winter. The size of the baseboard heating system does not provide adequate heating capacity for the building. Thus, it does not have the necessary temperature pickup on cold mornings, and it does not have the ability to use effectively the lower water temperatures available during winter months. For the first several years of operation, use of solar-heated water for protecting solar collectors from freezing also tended to lower the temperature of water available for the heating system.

During the winter of 1979-1980, a heat exchanger was installed so that a freeze protection medium (ethylene glycol) could be added to the collectors. Although this approach eliminated the danger of collector freezeup, a 5°C (9°F) temperature penalty resulted across the heat exchanger.

Single-glazed windows were originally installed in the building because NECAP computer energy data indicated that double-glazing would not be cost-effective. Nonetheless, even with inside temperatures of 22°C (72°F) or higher, cold drafts caused personal discomfort, and additional space heating was necessary. Storm windows were added in 1978 to help correct this problem.

Occupants complained of "stuffiness" at certain times. This always occurred on cool days when the air distribution system was in its economy cycle. Although large amounts of fresh air were brought into the building during these periods, the variable-volume terminal dampers reduced air circulation flow to less than 2.6 $(L/s)/m^2$ (0.5 cfm/ft^2). This situation was improved by adjusting the discharge air to a higher temperature to keep airflows higher. In addition, when the temperature dropped below a 22°C (72°F) in the office area, the variable-air-volume system pressure was reduced so that all variable volume terminal boxes were opened, allowing at least 2.6 $(L/s)/m^2$ (0.5 cfm/ft^2) circulation throughout the building.

Performance of Components

Figure 6 illustrates some of the thermal and energy characteristics of the SBTF that are monitored on a continuing basis. As can be seen in figure 6(a), temperatures are recorded for the office building, ambient air, hot water discharged from the solar field, and water in the storage tank at upper and lower levels. Figure 6(b) illustrates energy production and utilization data over a typical 3-day period during the summer. A key is present on each of these figures explaining some of the operating characteristics which are shown in the graphs.

Absorption chiller.- The type of absorption machine used in the SBTF is not subject to "freezeup" or crystallization of lithium bromide salts from low hot water temperatures, because pumping of the salt solution keeps concentration down. This is in contrast to small, unpumped "thermal lift" absorption chillers used in earlier solar demonstration projects. These unpumped units would often crystallize, resulting in unsatisfactory performance of the solar cooling system and thus unfavorably influencing the public image of solar cooling.

Table V shows the coefficient of performance (COP) for the absorption chiller on a monthly basis over a typical 1-year period. Cooling was not required during December, January, and February. During the remaining 9 months, COP values ranged from 0.40 to 0.65, with an annual average of 0.62. If the values during months of low cooling requirements (October, November, March, and April) are eliminated, the long-term coefficient of performance range is 0.59 to 0.65 for the period from May through September. These COP values are within the expected range of 0.6 to 0.7 for machines of this type.

The lithium bromide machine has been most effectively operated with some of the pumped (weak) solution bypassed to the absorber, thus reducing the solution flow through the generator. This results in a more concentrated solution being supplied to the spray heads in the absorber.

Hot water needed for the necessary chiller capacity of 211 to 352 kW (60 to 100 tons) can be obtained using 74°C to 96°C (165°F to 205°F) water. The chiller operation from the solar field has been satisfactory, especially when cooling tower water is a few degrees below normal design condenser water temperature.

The original machine had a two-pass heat exchanger in the generator. This allowed uniform boiling of the refrigerant in the generator, thereby reducing the chance of lithium bromide carryover into the condenser. The machine has been modified to allow hot water from the solar field to enter the generator at the same end where the strong hot solution is removed; thus, a counter flow circuit is established. Most of the boiling is now assumed to take place at the hot-water-inlet end of the generator chamber. Since the load is kept lower than 60 percent of the machine's rated capacity, there is little danger, and no indication, of salt carryover to the unit's condenser.

Solar collectors.- Table VI summarizes the performance of the solar collectors over a 12-month period. On a monthly basis, the efficiency of the collectors varied from 20 to 31 percent, with an average value of 26 percent.

In the SBTF, the tilt angle of the collectors is 32° from the horizontal, facing south, reflecting the emphasis on cooling for summer operation. This angle was determined by a modified NECAP program. As indicated earlier, the availability of hot water directly from the solar field is delayed until mid-morning because the collectors face south. Overall system performance would be improved by changing the azimuth of the collectors toward the east by 20° to 30°. This would result in a collector operation period that better coincides with the cooling needs or working hours in the SEB, even though less solar energy would be collected.

Although peak hourly collector efficiencies often exceeded 40 percent on sunny days, the 26-percent average achieved over the 12-month period is about as expected due to the high water temperature necessary for absorption chiller operation. Actual daytime collector efficiency was within 5 percent of predicted efficiency, as indicated in reference 3.

The field was inspected daily for leaks and/or malfunctioning controls. When required, repairs were made in the morning when the system is relatively cool. To interrupt flow later could cause the solution in the collectors to boil, thereby creating a dangerous situation for maintenance personnel.

One collector type, manufactured using a plywood cabinet and an aluminum plate absorber, failed early in 1977 and was removed from service. The failure occurred at a poorly designed, aluminum-tubing to aluminum-plate-coil connector due to external stresses. Other collector types were provided with additional support for the connector tubing. The collector type which failed also exhibited extensive degradation of the black paint coating.

The most serious and most commonly experienced problem was the external corrosion of the steel adapters used to connect the collectors to the flexible hoses. Moisture became entrapped within the insulation, and the interaction of moisture, steel, and insulation caused corrosive damage to the adapters, resulting in leaks - sometimes within 1 year. The field temperature was occasionally raised to 110°C (230°F) in an attempt to eliminate moisture, but the results were inconclusive regarding the effectiveness of this technique.

The piping and collectors are a mixture of steel, copper, and aluminum. Internal corrosion protection is provided by a chromate concentration of 1000 ppm, with the pH adjusted to 8.0. During the winter of 1977-1978, the chromate level dropped to about 600 ppm. This resulted in leaks in several steel collector panels. When chromate levels were again increased to 1000 ppm, no further problems with leakage were encountered. The internal pit-type corrosion is illustrated in figure 7. The photograph shows a section through a failed collector. The specific collector is made of two sheets of steel welded together and formed to obtain a water passage. The failure occurred on the absorber or hot side of the collector plate.

Controls.- The existing control system is somewhat more complicated than desirable or practical for routine operation; however, it does provide the high degree of flexibility required for high-temperature operation. Modifications will continue to be made not only to improve performance, but also to decrease operational complexity.

The sophisticated water-flow freeze-protection system works, but the risks are high in the Virginia climate due to the large number of hours of freezing and because a power failure could result in extensive, costly damage to the collectors. Utilization of antifreeze and installation of a heat exchanger were implemented during the winter of 1979-1980 as a solution to the freeze problem, but there was a sacrifice in system performance because of the losses associated with the heat exchanger.

Storage tank.- One problem experienced with the tank has been short-circuiting, that is, incoming water channeling to the tank outlet. When hot water is to be recovered from storage, cooler return water is piped into the bottom of the tank. This cooler water unfortunately short-circuits to the discharge. Some inversions of water temperature have occurred, as illustrated in figure 6(a). In 1979, baffles were installed to minimize the short-circuiting problem. Marginal improvement resulted.

The tank demonstrated very low thermal losses because of the vacuum jacket. Testing has indicated an average surface thermal heat transfe coefficient of less than 0.113 W/m^2-°C (0.02 Btu/ft^2-hr-°F). This value includes all appendages from the tank.

Flow measurement devices.- Problems continue to occur with the turbine meters used for flow measurements. These problems are caused by water-borne trash and are a continuing high maintenance cost.

The first problem was from the Teflon[2] tape used in making screwed piping connections. Long tape strands peeled off and attached to the turbine blades, either stopping or hindering their rotation. The second problem was turbine

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[2]Teflon: registered trademark of E. I. du Pont de Nemours & Co., Inc.

bearing failure due to wear. Within the first 4 months, a 100-percent failure rate was experienced. The situation was improved by adding a line filter in the water circuit. Unfortunately, within 2 years, the cloth filter and felt gasketing materials began to fail and, in turn, added to the problem.

Two (4-in.) ultrasonic flowmeters were installed at critical points. Although these meters are expensive ($600 for one meter and its associated electronics), few problems have been experienced as long as air is kept from the units.

DESIGN CONSIDERATIONS FOR FUTURE SOLAR COOLING SYSTEMS

On the basis of experience gained through operation of the SBTF for 4 years, the following comments are offered to those involved in the design of future solar cooling systems:

1. The proper selection of all components is highly important. Any weak element forces other components to operate inefficiently. Components should be adequately sized to utilize fully the lower temperatures available from solar fields. Undersizing of any one component will penalize the operation of all other components in the system.

2. Collector tilt and azimuth should be matched to the needs and location of the particular building. The azimuth should be directed so that maximum collector outputs occur during the working hours in the building. Periods of maximum energy production and energy utilization should coincide as much as possible.

3. Buildings can be cooled at considerably lower capacities per unit area than previously used. An old office standard was 6.6 m^2/kW (250 ft^2/ton), but today it is not unusual to get twice that area per unit of refrigeration.

4. The operation of an absorption chiller is extremely sensitive to the condenser water temperature. Experience gained in drier climates with lower condenser water temperatures may not necessarily be transferable to more humid climates.

5. Because high water temperatures from the collectors are important to the operation of the chiller, whenever possible, hot water from the solar field should be piped directly to the chiller to prevent temperature losses in the storage tank or heat exchanger.

6. Storage systems should be designed to capture and discharge the highest temperatures that can be produced from the collectors. A large extent of temperature stratification is possible in storage tank water if tanks are designed to prevent short-circuiting.

CONCLUSIONS

The general performance of the Solar Building Test Facility and its subsystems and components over a 4-year operational period has been discussed. From the operational period and the data provided for a typical year of operation, the following conclusions are made:

1. The Solar Building Test Facility project has demonstrated that solar cooling systems are technologically feasible.

2. The solar system provided 57 percent of the thermal energy required for heating and cooling over a representative 12-month period.

3. The average efficiency of the solar collectors was 26 percent on an annual basis.

4. Of the solar energy collected during 12 months, 46 percent was actually utilized. The average utilization rate was 82 percent for the months of June through September, when thermal energy was consumed for cooling only.

5. Pumped absorption chillers do not present the problems of crystallization that occurred with earlier unpumped models.

6. Water temperatures typically available from the solar field resulted in chilled water from the absorption machine with higher temperatures than the 7°C (45°F) design temperature normally used to cool office buildings. Nonetheless, a satisfactory working environment was provided by decreasing the dry bulb temperature in the occupied areas to compensate for the resultant high humidity.

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TABLE I.- COLLECTORS IN THE SOLAR FIELD: INSTALLATIONS AS OF MAY 1976 AND JULY 1980

Row	Original installation - May 1976			Installation as of July 1980		
	Manufacturer	Glazing	Coating	Manufacturer	Glazing	Coating
12	Chamberlain	2 glass	Black chrome	Chamberlain	2 glass	Black chrome
11	Chamberlain	2 glass	Black chrome	Chamberlain	2 glass	Black chrome
10	Chamberlain	2 glass	Black chrome	Chamberlain	2 glass	Black chrome
9	Chamberlain	1 glass	Black chrome	Chamberlain	1 glass	Black chrome
8	Chamberlain	1 glass	Black chrome	Chamberlain	1 glass	Black chrome
7	Chamberlain	2 glass	Black paint	Chamberlain	2 glass	Black paint
6	General Electric	2 Lexan[a]	Selective	General Electric	2 Lexan	Selective
5	Libbey-Owens-Ford	2 glass	Black paint	Libbey-Owens-Ford[b]	2 glass	Black paint
4	Martin Marietta	2 glass	Black anodized aluminum	Chamberlain[c]	2 glass	Black paint
3	Sun Source	1 glass	Black nickel	Sun Source	1 glass	Black nickel
2	Chamberlain	2 glass	Black paint	Chamberlain	2 glass	Black paint
1	Chamberlain	2 glass	Black paint	Owens-Illinois Sunpak	Vacuum tube	Selective
0	----------------	-------	-------------	Northrup tracker	Fresnel lens	Selective

[a]Lexan: trade name of General Electric Co.

[b]These collectors are no longer in service. They will be replaced in the near future with Lennox LSC18 collectors, which have single glass glazing and a black chrome coating.

[c]These collectors were in row 1 and were installed in row 4 after being repainted.

TABLE II.- PERFORMANCE OF THE SOLAR SYSTEM AT THE SBTF

Month	Energy used for heating		Energy used for cooling		Total thermal energy used		Solar energy used		Supplemental energy used (a)		% Building thermal energy from solar	Electric power used for lights and equipment, kW-hr
	GJ	Btu	GJ	Btu	GJ	Btu	GJ	Btu	GJ	Btu		
Sept. 77	0	0	197	187×10^6	197	187×10^6	134	127×10^6	[b]63	[b]60×10^6	68	78 000
Oct.	6	6×10^6	11	10	17	16	14	13	[b]3	[b]3	81	65 000
Nov.	11	10	5	5	16	15	16	15	0	0	100	68 000
Dec.	55	52	0	0	55	52	34	32	21	20	61	69 000
Jan. 78	[c]71	[c]67	0	0	71	67	23	22	[d]48	[d]45	33	70 000
Feb.	[c]64	[c]61	0	0	64	61	22	21	[d]42	[d]40	35	70 000
March	26	25	2	2	28	27	22	21	6	6	79	71 000
April	4	4	11	10	15	14	15	14	0	0	100	64 000
May	1	1	75	71	76	72	69	65	7	7	90	77 000
June	0	0	219	208	219	208	135	128	84	80	62	86 000
July	0	0	234	222	234	222	97	92	137	130	41	84 000
Aug.	0	0	264	250	264	250	137	130	127	120	52	101 000
Total	238	226×10^6	1018	965×10^6	1256	1191×10^6	718	680×10^6	538	511×10^6	[e]57 (av)	903 000

[a]Data adjusted for calibration error.
[b]Missing data extrapolated.
[c]Estimate for plenum heater energy added.
[d]Energy used for freeze protection subtracted.
[e]Annual basis.

TABLE III.- PERCENTAGES OF THERMAL ENERGY USED FOR COOLING

AND HEATING THE SEB

Month	Thermal energy used for cooling, percent	Thermal energy used for heating, percent
Sept. 1977	100	0
Oct.	63	37
Nov.	33	67
Dec.	0	100
Jan. 1978	0	100
Feb.	0	100
March	7	93
April	71	29
May	99	1
June	100	0
July	100	0
Aug.	100	0
Annual average	81	19

TABLE IV.- UTILIZATION OF COLLECTED SOLAR ENERGY

Month	Solar energy collected[a]		Solar energy used		Utilization of collected solar energy, percent
	GJ	Btu	GJ	Btu	
Sept. 1977	160	152×10^6	134	127×10^6	84
Oct.	115	109	14	13	12
Nov.	58	55	16	15	27
Dec.	79	75	34	32	43
Jan. 1978	101	96	23	22	23
Feb.	111	105	22	21	20
March	161	153	22	21	14
April	187	177	15	14	8
May	145	137	69	65	47
June	159	151	135	128	85
July	134	127	97	92	72
Aug.	162	154	137	130	84
Total	1572	1491×10^6	718	680×10^6	[b]46 (av)

[a]Data developed from "on the hour" rates.
[b]Annual basis.

TABLE V.- LONG-TERM COEFFICIENT OF PERFORMANCE (COP)

FOR THE ABSORPTION CHILLER

Month	Thermal energy used by absorption unit in cooling		Cooling energy produced by absorption unit		Monthly COP
	GJ	Btu	GJ	Btu	
Sept. 1977	197	187 × 10^6	120	114 × 10^6	0.61
Oct.	11	10	4	4	.40
Nov.	5	5	3	3	.60
Dec.	0	0	0	0	----
Jan. 1978	0	0	0	0	----
Feb.	0	0	0	0	----
March	2	2	1	1	.50
April	11	10	4	4	.40
May	75	71	44	42	.59
June	219	208	142	135	.65
July	234	222	139	132	.59
Aug.	264	250	171	162	.65
Total	1018	965 × 10^6	628	597 × 10^6	[a]0.62 (av)

[a]Annual basis.

TABLE VI.- EFFICIENCY OF THE SOLAR COLLECTORS

Month	Solar energy available		Solar energy collected[a]		Collection efficiency, percent
	GJ	Btu	GJ	Btu	
Sept. 1977	603	572×10^6	160	152×10^6	27
Oct.	483	458	115	109	24
Nov.	290	275	58	55	20
Dec.	277	263	79	75	29
Jan. 1978	410	389	101	96	25
Feb.	459	435	111	105	24
March	601	570	161	153	27
April	603	572	187	177	31
May[b]	464	440	145	137	31
June[b]	619	587	159	151	26
July[b]	553	524	134	127	24
Aug.[b]	608	576	162	154	27
Total	5970	5561×10^6	1572	1491×10^6	[c]26 (av)

[a]Data developed from "on the hour" rates.

[b]Solar field reduced from 1064 to 974 m^2 (11 450 to 10 480 ft^2).

[c]Annual basis.

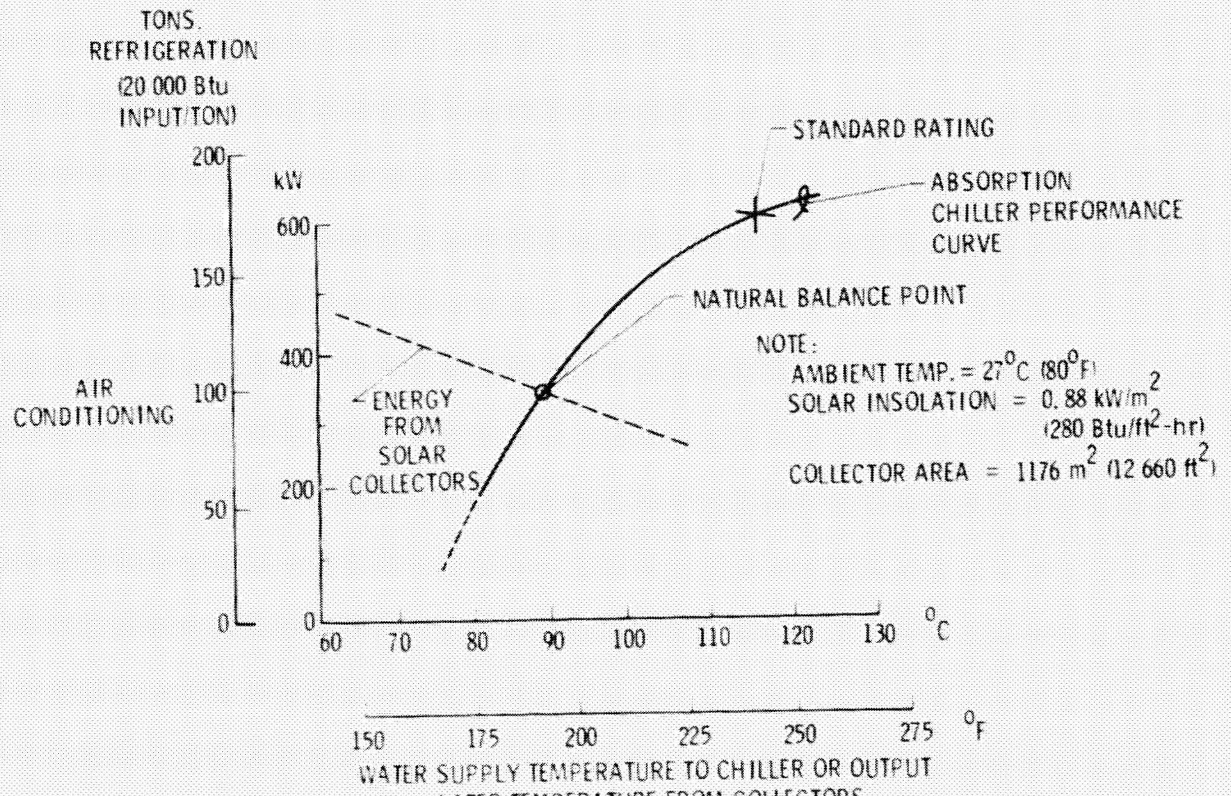

Figure 1.- Effect of water temperature on the capacities of the solar collectors and the absorption chiller.

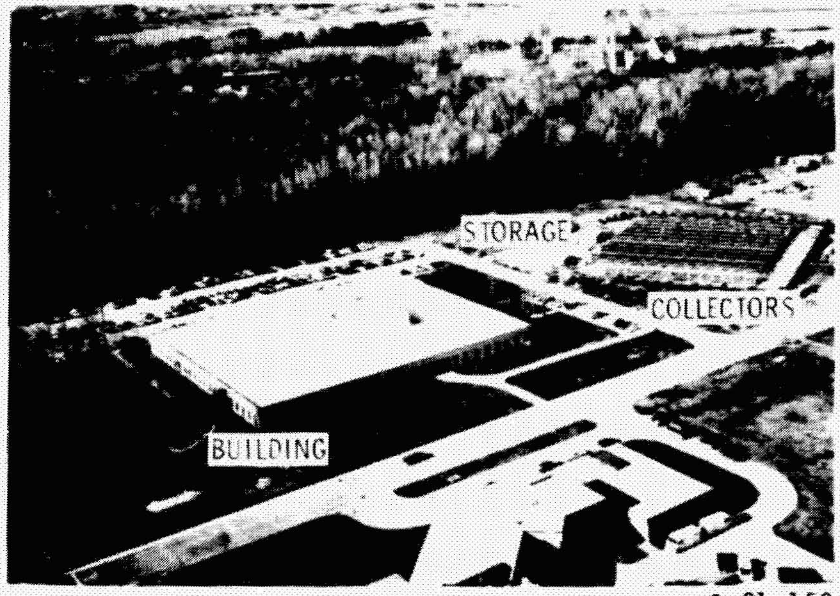

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Figure 2.- Solar Building Test Facility.

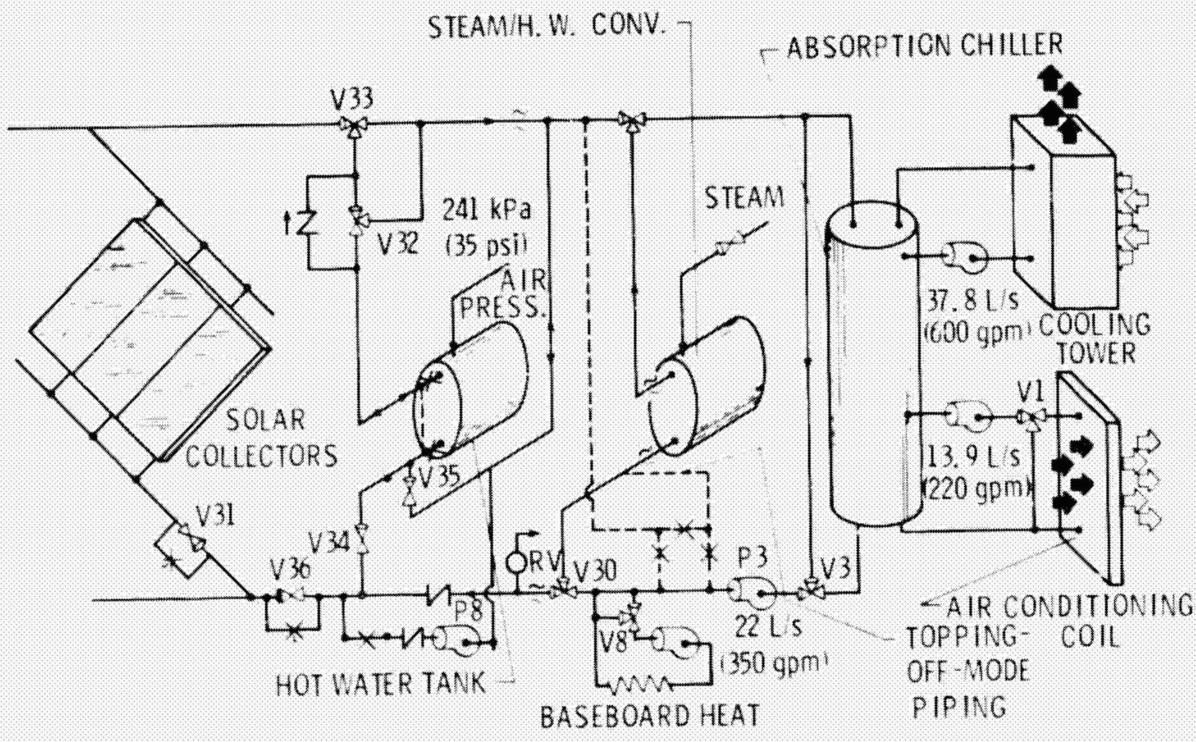


Figure 3.- Schematic flow diagram of the piping and controls at the Solar Building Test Facility.

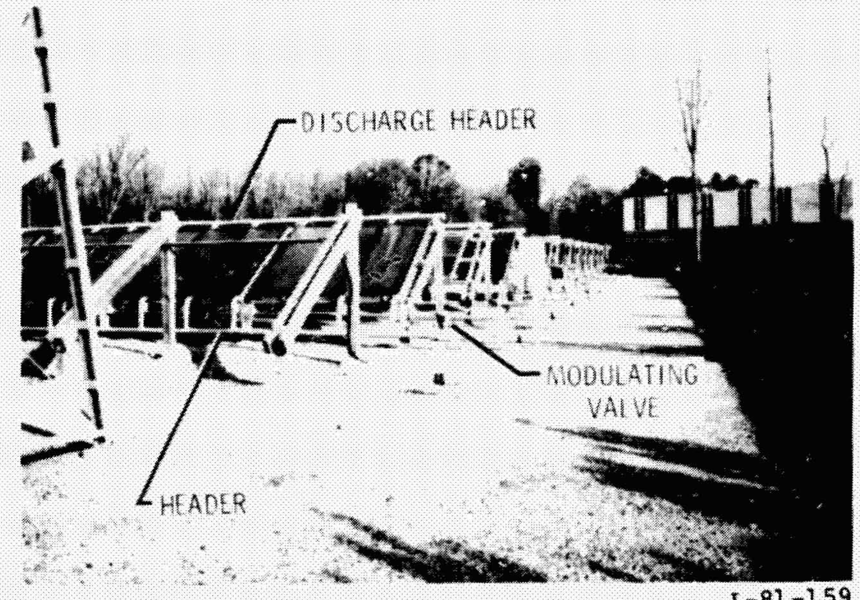


Figure 4.- Collectors in the solar field.

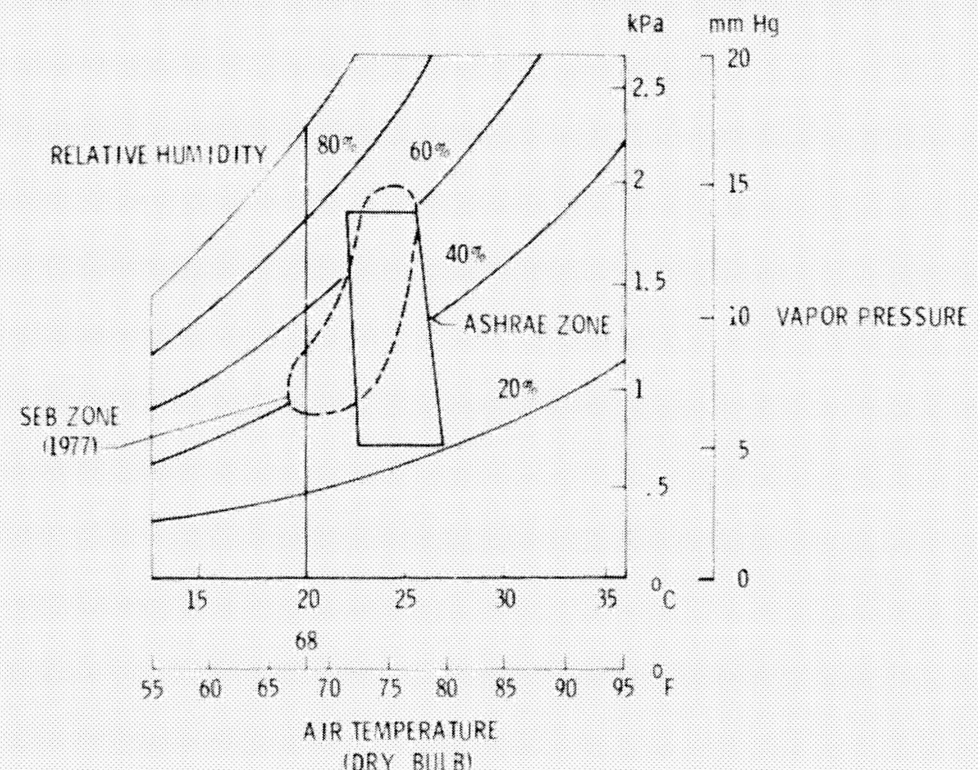
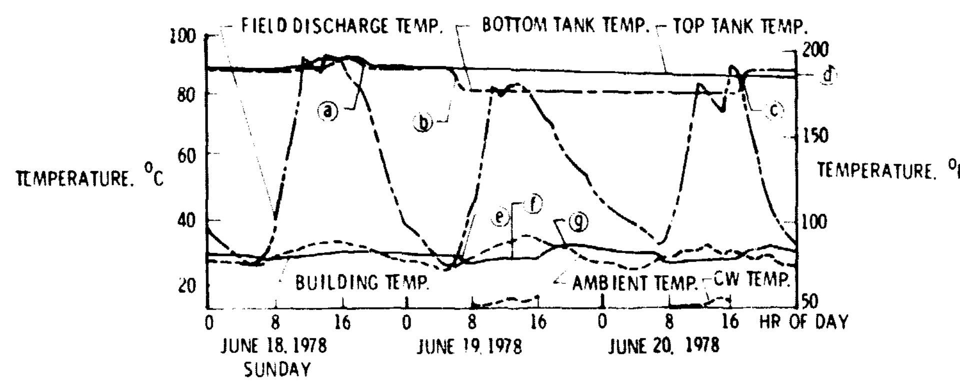


Figure 5.- Range of temperature and humidity conditions in the SEB during 99 percent of the working hours compared with the comfort zone of ASHRAE Standard 55-74.

Key:

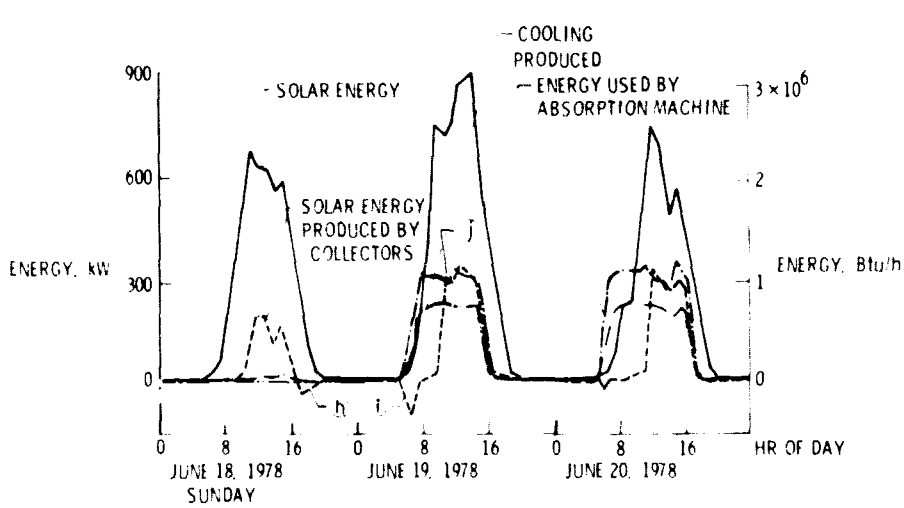
(a) Weekend energy storage, very little stratification due to mixing.
(b) Energy for the chiller is taken from the tank while colder water enters the bottom of the tank.
(c) Simultaneous absorption machine operation and energy storage.
(d) Water temperature inversion in the storage tank.
(e) Quick morning cooldown of the building.
(f) Temperature ramp during the day.
(g) A slow temperature rise with the air c .iditioner off and most of the lights on for janitorial cleanup.



(a) Temperatures monitored.

Key:

(h) A measured energy loss in the collectors when the small circuiting pump, P8, is left on.
(i) A measured energy loss in the collectors due to leakage of hot water to collectors past control valves.
(j) Operation of absorption chiller directly from the solar field, which usually begins around 10:30 a.m. (DST).



(b) Energy production and utilization monitored.

Figure 6.- Hourly operating data.

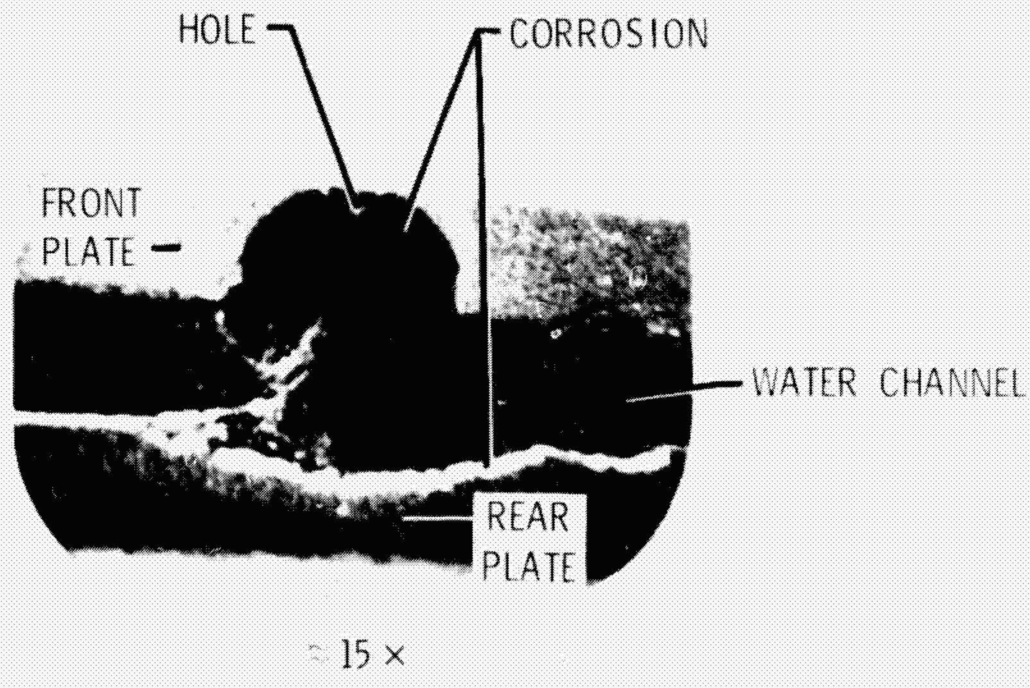


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Figure 7.- Pit-type corrosion in a steel collector plate.